AFRL-HE-WP-TR-2006-0128

Effects of a Combined 3-D Auditory/visual Cueing System on Visual Target Detection Using a Helmet-Mounted Display

Carlos Pinedo
Laurence Young
Man Vehicle Laboratory
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge MA 02139-430

Robert Esken
Human Effectiveness Directorate
Air Force Research Laboratory
Wright Patterson AFB OH 45433-7947

August 2005

Final Report for the period December 2003 to August 2005

Approved for public release; distribution unlimited

Air Force Research Laboratory
Human Effectiveness Directorate
Warfighter Interface Division
System Control Interfaces
Wright Patterson AFB OH 45433

NOTICE

TECHNICAL REVIEW AND APPROVAL

AFRL-HE-WP-TR-2006-0128

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

FOR THE DIRECTOR

//signed//

DANIEL G. GODDARD
Chief, Warfighter Interface Division
Air Force Research Laboratory

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
1 August 05	Final	December 2003 – August 2005

4. TITLE AND SUBTITLE
Effects of a Combined 3-D Auditory/visual Cueing System on Visual Target Detection Using a Helmet-Mounted Display

5a. CONTRACT NUMBER
In-House

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62202F

6. AUTHOR(S)
Carlos Pinedo
Laurence Young
Robert Esken *

5d. PROJECT NUMBER
7184

5e. TASK NUMBER
60

5f. WORK UNIT NUMBER
01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Man Vehicle Laboratory
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge MA 02139-4307

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Materiel Command *
Air Force Research Laboratory
Human Effectiveness Directorate
Warfighter Interface Division
System Control Interfaces
Wright Patterson AFB OH 45433-7947

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/HECI

11. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFRL-HE-WP-TR-2006-0128

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

AFRL/PA Cleared 9-18-06, AFRL/WS 06-2214.

14. ABSTRACT
Past research has shown that spatial orientation and situational awareness benefits are related to the use of HMD symbology and increased performance with localized audio. The research on HMDs includes looking at the benefits of off-boresight symbology for target search and attaches tasks, developing a methodology for evaluating off-axis HMD ownship information, and the development and evaluation of the NDFR symbology for on/off-boresight viewing. The localized auditory research includes looking at the benefits of augmenting the Terrain Collision Avoidance System (TCAS) with 3-D audio cues, using audio cues both spoken and non-spoken to help guide a visual search, and the effects of high acceleration on audio localization. The conclusions from this research are described below.

15. SUBJECT TERMS
HMD, Terrain Collision Avoidance System (TCAS), 3D audio, Non-Distributed Flight Reference (NDFR), Head –up display (HUD), Subjective Workload Dominance Technique (SWORD)

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Clifford Combs
U	U	U	SAR	**46**	**19b. TELEPONE NUMBER (*Include area code)***

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI-Std Z39-18

This page intentionally left blank.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

PREFACE

This research was funded and supported by the Air Force Research Laboratory at Wright-Patterson Air Force Base and carried out at the Man Vehicles Laboratory at the Massachusetts Institute of Technology. The study was conducted under the supervision of Dr. Laurence Young of the Apollo Program of Astronautics at MIT. Data analysis support was provided by Dr. Alan Natapoff of the Department of Aeronautics and Astronautics at MIT. Additional software and technical support was supplied by Mr. Robert Esken and the Human Effectiveness Directorate of AFRL.

INTRODUCTION

Spatial disorientation and loss of situational awareness continue to be a leading cause of military aircraft accidents. Currently, pilots are dependent solely on their visual and vestibular systems for attitude information, both of which can be easily misled. The proposed solution to this spatial disorientation problem is to increase the avenues through which information is given to the pilot. This can be done through the development of the helmet-mounted display (HMD) to provide better and continuous visual cues, the use of three-dimensional audio for target detection and terrain collision avoidance, and the use of tactile sensors for attitude information. This study will look at the HMD and the use of 3-D audio for target detection.

HMDs allow the pilot to look longer off-boresight during air-to-air and air-to-ground tasks. Research has been conducted to develop HMD symbology that provides effective target cueing information while minimizing visual occlusion. The Non-Distributed Flight Reference (NDFR) symbology has proven to be an effective symbology in allowing the pilot to look longer off-boresight while maintaining flight performance on par with current military standard displays. Research into auditory localization has shown that target acquisition time decreased significantly with the use of a combined 3-D audio and visual cueing system. The objective of this study is to determine the combined effects of the two systems by, first, looking at the flight performance benefits of the NDFR symbology; and second, by studying the target acquisition benefits of using a combined 3-D audio/visual cueing system during a visual target search task.

Background

Past research has shown that spatial orientation and situational awareness benefits are related to the use of HMD symbology and increased performance with localized audio. The research on HMDs includes looking at the benefits of off-boresight symbology for target search and attack tasks, developing a methodology for evaluating off-axis HMD ownship information, and the development and evaluation of the NDFR symbology for on/off-boresight viewing. The localized auditory research includes looking at the benefits of augmenting the Terrain Collision Avoidance System (TCAS) with 3-D audio cues, using audio cues both spoken and non-spoken to help guide a visual search, and the effects of high acceleration on audio localization. The conclusions from this research are described below.

Helmet-Mounted Display Research

The Air Force currently equips most combat aircraft with a Head-Up Display (HUD) which gives the pilot attitude information while looking on boresight (straight ahead). The HUD however fails to give the pilot any attitude information during tasks that require them to look off-boresight. Therefore the use of HMDs was proposed as a means to continuously provide the pilot with attitude information. Nonetheless having continuous attitude information through an HMD does not equate to better performance or an increase in situational awareness.

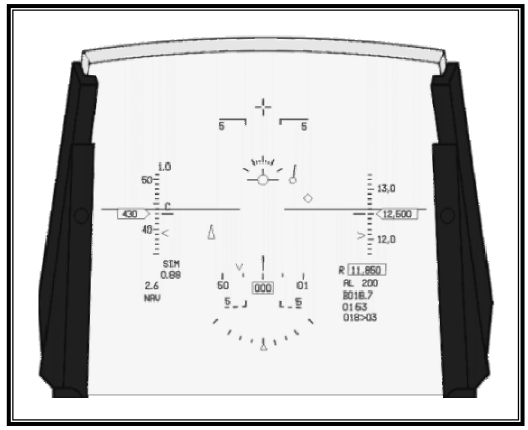

Figure 1: Military Standard HUD

For this reason the Air Force conducted studies comparing the use of HMDs to the current HUD. In one such study, Geiselman and Osgood[1] compared the utility of three off-boresight helmet-mounted display symbology information levels for high angle target search and intercept during a simulated air-to-air engagement. The information levels included: (1) HUD presentation of both ownship status and target location; (2) HUD status plus HMD target location; and (3) HUD status plus HMD target location plus HMD ownship status. Four different attitude symbology elements were evaluated within ownship status level. The experiment contained two phases. The first was a target search task where the subjects visually searched the surrounding airspace in order to locate and acquire radar lock on an airborne target while maintaining their initial aircraft parameters of 5000 feet altitude, 480 knots airspeed, and heading of 0°. The second phase was the attack phase where the subjects maneuvered the aircraft to bring the target within the launch envelope; the trial was successful when a good launch was accomplished. During both the search and attack phases, pilots were able to look longer off-boresight with the use of the HMD without any decrease in performance. "The capability and comfort to search more surrounding area for a longer period of time, while not accruing a performance cost, may be interpreted as a potential [situational awareness] benefit."[1] A modification of the Subjective Workload Dominance Technique (SWORD) was used to record subjective ratings of situation awareness benefits. The SWORD data found no differences among symbology formats within the HMD ownship status level. However, subjects stated that ownship status information should be included in the symbology.

The previous study showed that pilots with HMD spent more time off-boresight versus pilots using a HUD; hence the HMD should display information that pilots would normally obtain from looking forward into the cockpit. This information is intended to keep the pilot spatially oriented. A study conducted by Geiselman, Havig, and Brewer[2] describes the design and evaluation of the NDFR symbology, which provides the pilot with continuous ownship status information, for off-boresight viewing. Three symbology sets were

compared: the standard HUD symbology, the Visually Coupled Acquisition Targeting System (VCATS), and the NDFR symbology.

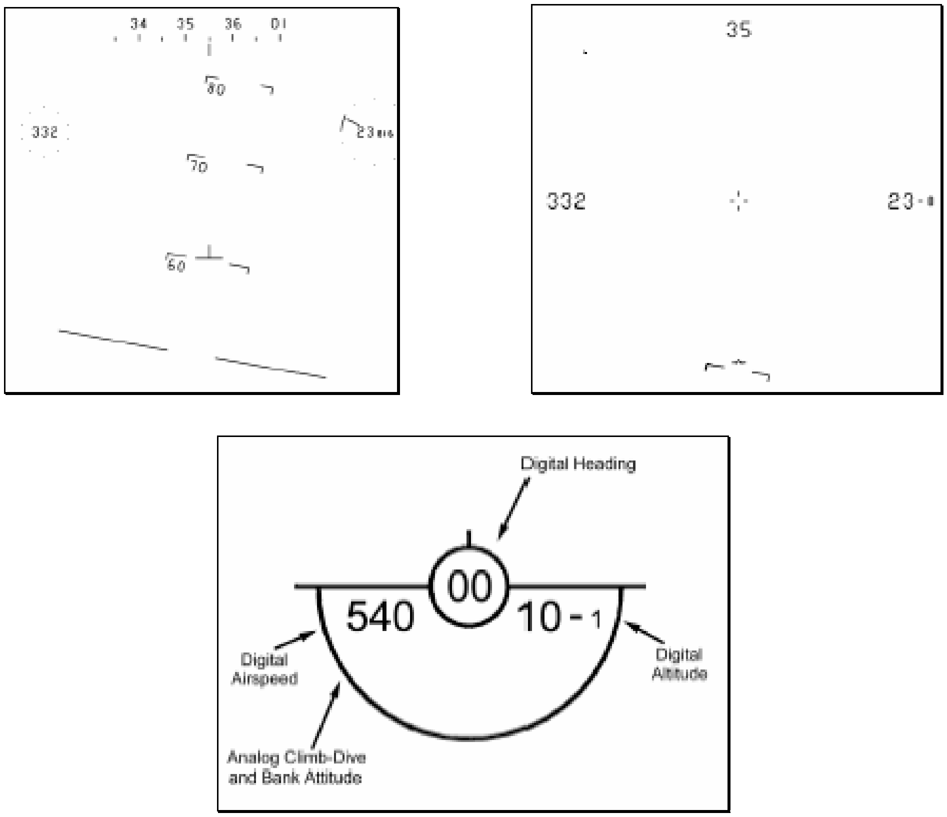

Figure 2: Military Standard HUD, VCAT, NDFR

The experiment consisted of the subjects recalling ownship information from static presentations of the symbology sets for specified exposure times. The subjects also gave subjective feedback concerning the sets, such as their confidence in determining ownship status. The results show that the NDFR symbology afforded better information interpretation. The NDFR appears to provide extra information processing capacity compared to the VCATS symbology. Subjective feedback is consistent with these findings in that subjects felt more confident in determining ownship information with the NDFR display. The ability for pilots to quickly assess ownship information to establish an accurate perception of orientation may be a possible situational awareness benefit. Use of the NDFR symbology appears to reduce pilot workload when establishing spatial orientation, allowing the pilot to perform other tasks while maintaining flight performance.

Further studies by Havig, Jenkins, and Geiselman looked at how attitude information should be displayed when off-boresight; two options are forward or line of sight (LOS).[3] The "forward" symbology displays on-boresight attitude information when looking off-boresight, while the "LOS" symbology displays attitude information congruent with the visual scene. They investigated five different symbologies (standard HUD, VCATS, ASAR, Theta Ball, and NDFR). The experiment consisted of two different tasks, with the pilots performing the

task either facing the monitor or rotated 90º and looking over their shoulder (off-boresight). In the first task, pilots maintained straight and level flight with simulated turbulence. The second task had pilots interpret a static representation of their attitude and respond via a key press; then the display went live and they had to fly to a new commanded attitude. The NDFR symbology resulted in better control when off-boresight and forward was better than LOS. The reaction times for choosing the correct attitude in the second part of the experiment were fastest using the NDFR. The NDFR during attitude recovery provided a significantly faster initial stick input even though the overall performance was equal for all symbol sets. The NDFR symbology performed as well if not better in providing ownship information. Pilots were able to keep a more accurate perception of orientation when using the NDFR symbology. Also, the faster reaction times may allow pilots to recover from situations where they may be spatially disoriented.

The NDFR symbology allows pilots to look longer off-boresight during air-to-air and air-to-ground tasks during *simulated* trials. A study by Jenkins, Thurling, Havig, and Geiselman[4] looked at quantifying pilot performance during *in-flight* operationally representative tasks: air-to-ground, air-to-air, and unusual attitude recoveries. The symbology sets evaluated were the standard HUD, the NDFR, and the VCATS. The China Lake Situational Awareness (CLSA) rating scale was used to measure pilot situational awareness for each symbology and the Modified Cooper-Harper Rating (MCHR) scale was used to measure workload. Pilots were able to spend longer time looking off-boresight with the HMDs; however, the NDFR was the only one that had no decrease in performance. This was true for both air-to-ground and air-to-air tasks. The VCATS symbology allowed the pilots to look longer off-boresight, but it failed to provide adequate situational awareness resulting in a decrease in performance. For the air-to-ground task the situational awareness rating was equal for the HUD versus the NDFR symbology sets while the VCATS performed significantly worse. These results were also seen in the workload assessment. For the air-to-air tasks NDFR had the best situational awareness and workload ratings. Both the NDFR and the VCATS symbology sets allowed significantly faster reaction times for first significant stick input. The results of the flight test are consistent with the ground simulation trials from previous studies.

Based on the recommendations of the flight test, changes were made to the NDFR symbology. Two variants of the NDFR format as well as the standard HUD and baseline NDFR format were examined during two simulated operationally representative air-to-air intercept tasks that employed the use of an HMD for the off-boresight visual acquisition of a target aircraft.[5] The objective of the study was to evaluate the display formats for off-boresight HMD use in conveying rate of change or trend information to the pilot. It was hypothesized that pilots would maintain better control if they had the ability to detect changes in airspeed and altitude. After completing both trials, a low-slow intercept and a High Value Airborne Assets defense trial, the pilots were asked to rate their situational awareness using the CLSA scale and workload using the MCHR scale. The NDFR/Odometer symbology proved to be the best symbology for providing trend information and received the best MCHR rating. The NDFR/Odometer symbology allowed the greatest time off-boresight, performed equally to the HUD and other NDFR symbologies, and was the preferred symbology of pilots.

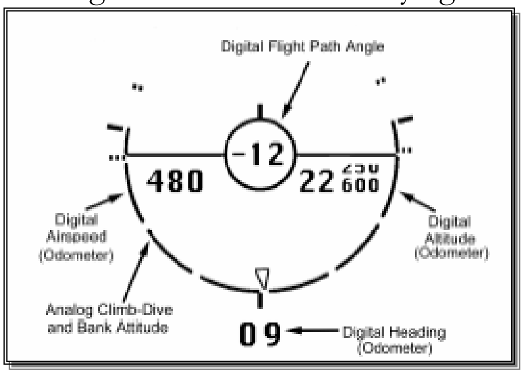

Figure 3: NDFR/Odometer

Geiselman conducted another study whose purpose was to develop a methodology for evaluating off-axis HMD ownship information.[6] Three experiments were discussed in the paper; one (Geiselman, Osgood, 1994)[1] has already been discussed. The other two experiments were a low altitude flight task, with and without manipulation of off-axis ownship information, and an air-to-air target cueing study.

The first study included a simulated, low-level, high-speed, airborne surveillance/reconnaissance mission. A with and without manipulation of a simple off-axis ownship information display was performed. Pilots were instructed to maintain a 400 ft, 480 knot flight profile along a prescribed heading. The consequences for excess altitude deviations were ground collision and the threat of surface-to-air missiles. Subjects maintained altitude and heading while searching for airborne threats and took evasive action if fired upon. The trial consisted of a search phase and a monitor phase. During both phases, HMD-presented ownship information resulted in the pilots looking farther off-axis for a longer period of time without any decrease in performance. Two other interesting effects were found. During the 142 trials of the experiment, no ground strikes occurred when HMD ownship information was available. Without the HMD, five ground strikes were recorded. Secondly, a possible benefit to situational awareness was seen by looking at a snapshot of the pilot behavior at the instant a significant event occurred, for example a hostile missile launch. As seen in Figure 4, pilot LOS when HMD aided tended to be at angles much closer to the location of the threat when the missile was launched. In fact, during trials where HMD information was not available, the average LOS angle actually resulted in the hostile aircraft location being beyond the reasonable field of view of the pilot (left graphic in Figure 4).

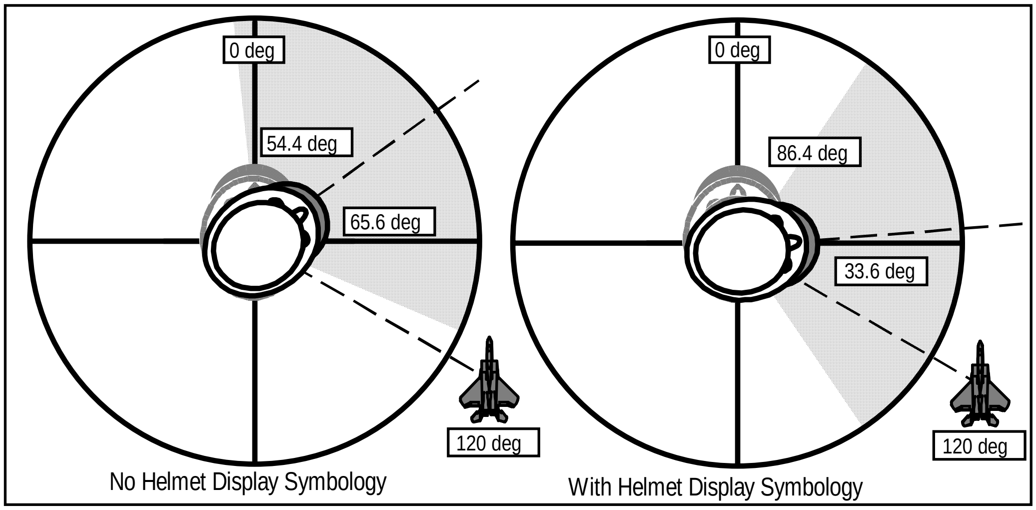

Figure 4: Pilot LOS during Critical Event with and without an HMD Aid

In developing the methodology for evaluating off-axis HMD ownship information, Geiselman et al.. also reviewed another experiment which investigated the effects of HMD-resident target location information reference frame during air-to-air target acquisition and intercept tasks. The objective of the study was to determine if off-boresight locator information should indicate the position of the target relative to the nose of the aircraft (fly-to), relative to the nose on the pilot's face (look-to), or a combination of the two. The HMD did include ownship status information. The experimental trials consisted of a search phase and an attack phase. For both tasks the pilots looked farther off-boresight when HMD target location information was available. Although not supported by the performance data, the subjective results strongly suggested that the pilots favored the combination (multiple coordinate reference frame).

The overall conclusions from the HMD literature can be summarized as follows: 1) Pilots look longer off-boresight when HMD is available compared to using only the HUD for both air-to-air and air-to-ground tasks. 2) There was no decrease in performance due to looking longer off-boresight. 3) The pilots preferred that off-axis ownship status information be included within the HMD symbology set. 4) The HMD symbology should minimize visual occlusion. 5) The NDFR symbol set is the preferred symbol set for conveying ownship information in the HMD, as compared to the standard HUD and VCATS. 6) When looking off-boresight the symbology should be forward referenced. 7) The NDFR should include trend information.

Localized Audio Research

Pilots are saturated with visual information. However, humans have at their disposal two other modalities rarely utilized, auditory and tactile. Auditory cues are currently used in aircraft primarily as warnings and alarms. Localized audio is being developed to aid in target acquisition and detection, improve terrain collision avoidance, and help with traffic awareness.

When humans hear a spatial audio sound the signal is evaluated depending on its elevation and azimuth. Humans can easily distinguish sounds emanating from their right or left because the signal is mainly shifted in time and the brain uses the frequency shift from right to left ear to determine location. To determine elevation information from an audio signal, the brain uses the difference in frequency attenuation between the two ears, caused by the pinna (i.e., the shape of the ear). The current method for producing virtual localized audio cues involves the use of an anechoic chamber with speakers located at various elevations and azimuths (often in a sphere around the subject) and a microphone located in the subject's inner ear. The microphone is used to record the frequency attenuation produced by the subject's pinna for each speaker location. These recordings are used to develop what is known as Head Related Transfer Functions (HRTFs) which are later used to produce virtual localized audio signals through headphones. When using this method the HRTFs developed are specific to the subject. Generic HRTFs can be obtained by using a mannequin in lieu of a human subject.

Past research into headphone-delivered three-dimensional audio suggests that optimal localization performance results from the combination of the following three factors: 1) head-tracked virtual stimuli, 2) synthesis of a virtual room, and 3) use of individualized as opposed to generic HRTFs.[7] The purpose of this study was to directly compare all these factors -- something that had not yet been done in a single study. The experiment evaluated auditory localization, externalization of sound images, and perceived realism. A speech stimulus was given with three levels of reverberation: anechoic, early reflections, and full reverberation. Both individualized and non-individualized HRTFs were studied along with a continuously updating head tracker whose information was used to update the position of the stimuli or was disregarded. Reverberation was found to have a significant effect on azimuth and elevation errors. Stimuli which include reverberation will yield lower azimuth errors, but at the sacrifice of elevation accuracy. Head tracking and individualized HRTFs significantly reduced the occurrence of reversals; however, there was no other clear advantage in using individualized HRTFs.

In 1999 Bolia et al..[8] conducted an experiment to evaluate the effectiveness of spatial audio displays on target acquisition performance under three scenarios: no spatial audio, free-field spatial audio, and virtual spatial audio. Subjects performed a visual search task with and without the aid of spatial audio. Results indicated that visual search times decreased significantly with the aid of free-field or virtual spatial audio. The subjects sat in a sphere where at the apex of every strut there existed a speaker and four LEDs. The number of

LEDs lit determined whether a target or a distracter was present. Two or four LEDs lit meant that a target was present, while one and three LEDs lit meant that a distracter was present. The subject responded when a target was present and the number of LEDs lit was two or four. The free-field audio performed better than virtual audio, which can be attributed to defects inherent in the HRTF collection technique, the use of non-individualized HRTFs, and the spatial resolution of the HRTFs. People localize well in azimuth with non-individualized transfer functions, but they make fewer front-back reflections and are more accurate in elevation with their own HRTFs. The study demonstrated a reduction in search time by a factor of six or more for high-complexity searches with the use of virtual spatial audio cueing without a corresponding reduction in the accuracy of target identification.

Flanagan et al..[9] combined localized audio with an HMD to investigate search time for a visual search task with targets outside the field of view (FOV). The auditory signal was either presented at the beginning or continually updated. Three scenarios were tested: visual cue, transient audio cue, and updating audio cue. The updating audio cue was more effective than the transient audio cue and was as effective as the visual cue in reducing search time. Subjects with no previous HMD experience were used. The transient audio was three short bursts, while the updating audio was a single noise burst every eight seconds. The visual display was a sighting circle with an arrow pointing to the target. The participant placed a red sighting circle over the white target for 0.5s. The ability to localize elevation is poorer and the incidence of front-back reflections higher when listening to virtual audio than under free-field listening conditions.

Further research into the use of localized audio and HMDs for visual search tasks was conducted by Nelson et al..[10] In this investigation the visual displays were either a wide FOV dome or an HMD and were accompanied by localized, non-localized, or no auditory information. Localized auditory information provided significant increases in target detection performance and significant reductions in workload ratings as compared to no auditory or non-localized audio. Localized audio resulted in more efficient search strategies. Targets approached from outside the field of view from a random direction. The participants pressed a mouse button when they detected a target. The participant also marked the location of the target with a head-slaved cursor. Subjects completed the NASA Task Load Index for workload. All metrics of performance -- efficiency; workload, and head motion – revealed a significant advantage for conditions in which localized auditory cues were provided. The reduction in head motion and velocity may improve pilot performance in high-G environments.

Visual search tasks were not the first use for localized audio; Begault and Pittman[11] used localized audio to improve upon the current Terrain Collision Avoidance System (TCAS). In their study they compared the current head-down TCAS system to a head-up audio TCAS system by measuring the time needed to capture visual targets. Ten commercial airline crews were tested under full-mission simulation conditions and were given either the standard visual-audio TCAS advisory or a 3-D aural advisory (the 3-D aural advisory did not include a

map display). The target remained at a fixed distance and speed relative to the subjects to eliminate differences between crews as a function of aircraft movement. The aural alert consisted of a non-speech pre-advisory and a voiced "TRAFFIC-TRAFFIC". The elevation cues were exaggerated because elevation judgments are often compressed relative to the actual target positions when listening through non-individualized HRTFs. However azimuth was not exaggerated. The results show that the use of 3-D audio significantly reduced the acquisition time by 500 ms. The results were comparable to past research done by Begault, and there appear to be no significant benefits of exaggerating the stimuli in azimuth.

Begault followed up on the previous experiment by adding 3-D audio to the visual display instead of replacing it.[12] Each crew flew the route twice, once with the addition of 3-D audio and once without. The results of this experiment agree with the past experiments in that the addition of 3-D audio helped reduce target acquisition time (225-749 msec). The experiment was done under the same condition as the previous experiment. Though the improvement in time is not great, the workload was relatively light, and it could be that in a high-workload situation one would see greater benefits of using 3-D audio cues. One interesting thing that was found in the experiment is that pilots did not utilize the elevation cue effectively, presumably because the successful perception of elevation cues from HRTFs is more difficult than azimuth. The suggestion made is that the aural stimuli should include location, for example "TRAFFIC, HIGH."

Combining localized audio and visual displays have proven to be effective in improving performance for the TCAS. Simpson et al.[13] looked at the performance benefits of a combined visual and audio display in an experiment where the subjects were required to acquire and identify a target under four conditions: 1) no display; 2) a visual display combined with a non-spatialized warning sound; 3) a visual display combined with a clock-coordinate speech signal; and 4) a visual display combined with a spatialized auditory warning sound. The subjects participated in a fully-immersive simulated flight task. For the no-display condition, subjects had to search without any aid, while in the other three conditions a Traffic Advisory System (TAS) provided the subject with information about the presence, relative altitude, and direction of the target. For the visual with clock-audio condition, the TAS system was augmented by a non-spatialized audio cue indicating clock direction, elevation, and distance of the target, for example "traffic, 9 o'clock high, 1 mile." In the TAS with 3D audio condition, the visual TAS display was supplemented with a spatialized audio cue that consisted of a chirp signal and a verbal cue indicating the relative elevation of the target (e.g., "traffic, low"). The distance corresponded to the vocal effort of the stimuli, with shouted speech indicating distant targets and conversational speech indicating close targets. The target aircraft was on a head-on collision path with the subject. No collisions occurred in the TAS-clock and TAS-3D audio conditions. The data show that the TAS-3D audio always led to the fastest response times and that the advantage of TAS-3D audio was greater when the targets were located in the rear hemisphere.

This past research has demonstrated the utility of virtual 3-D auditory displays for tasks that are relevant to air combat: 1) enhancing visual target detection and identification; 2)

increasing the effectiveness of collision avoidance displays; 3) improving the monitoring of simultaneous communication signals; and 4) alleviating problems associated with visual detection tasks in helmet-mounted displays. However no study has yet to address the effectiveness of 3D auditory displays under high levels of sustained acceleration. Nelson et al.[14] evaluated the ability to localize a virtual audio source during exposure to 1.0, 1.6, 2.5, 4.0, 5.6, and 7.0 $+G_z$ for auditory cues along the horizontal plane (elevation of 0°). The Dynamic Environment Simulator was used to simulate the acceleration stresses often encountered by pilots. The subjects used a right-hand knob to rotate a radius vector to the perceived azimuth. There were an equal amount of cues for each subject in each spatial quadrant of the horizontal plane. Both the average localization error and the percentage of reversal confusions indicated that increase $+G_z$ level did not correlate to reduction in ability to localize in the horizontal plane. It wasn't until subjects experienced 7.0 $+G_z$ that any significant increases in average localization error were found. Thus it appears that the use of 3-D audio displays will not be compromised by conditions of high acceleration, which are often experienced during tactical air combat environments.

The research conclusions from the localized audio literature are: 1) Three-dimensional auditory cues can reduce the time it takes to acquire targets in space with no apparent reduction in the accuracy of target acquisition. 2) Humans can localize better in azimuth than in elevation and degradation in elevation increases with the use of non-individualized HRTFs. 3) Greater reductions in time were found when the auditory cue was continuously updated as opposed to transiently; however, no comparisons were made between continuously updating and human speech. 4) Localized audio resulted in more efficient search strategies, meaning less head movement. 5) Non-individualized HRTFs led to an increase in front-back reversals compared to individualized HRTFs. 6) A subject's ability to localize sound is not degraded under high accelerations.

METHODS

It is the objective of this study to investigate the combined benefits of the NDFR symbology and three-dimensional audio cues for target acquisition tasks in a stationary simulator using a helmet-mounted display. Past research has shown that use of HMDs leads to more time spent looking off-boresight and less time referencing cockpit displays without any change in performance. Three-dimensional audio research has demonstrated that the use of a combined visual/audio system can decrease subject reaction time and increase performance. Visual-audio systems performed better than visual or audio systems alone. In this study subjects flew in a simulator while looking for targets using visual, audio, or multimodal visual-audio cues. The effectiveness of the NDFR in providing attitude information quickly and succinctly will be compared to the combined target cueing systems ability to reduce visual search time.

Participants

Twenty volunteers consisting of male and female MIT affiliates participated in this experiment. The volunteers had adequate eyesight and no significant hearing impairments. The subjects ranged from experienced pilots to people with no prior flying experience.

Experiment

The subjects flew an aircraft in a desktop simulator while acquiring targets in as short a time as possible. Two independent variables were manipulated. The first was the aircraft attitude symbology set. The two symbologies utilized were Military Standard (Mil-Std) symbology and the Non-Distributed Flight Reference (NDFR) symbology. The second independent variable was the target location cueing type. The three levels of cueing conditions were audio only, visual only, and combined audio/visual. The six resulting conditions are shown in Table 1.

Attitude Displays	Target Cues
Military Standard	Visual Only
	Auditory Only
	Combined Visual/Audio
Non-Distributed Flight Reference	Visual Only
	Auditory Only
	Combined Visual/Audio

Table 1: Experiment Conditions

The dependent variables were search time and flight performance. Search time is defined as the time it takes the subject to bring the target within the helmet-mounted aim-sight reticle from trial initiation. Flight performance was determined by the subject's deviation from a commanded heading and altitude.

The subjects were presented with targets from 15 locations. Half of the subjects began the trials with the Mil-Std attitude display and the other half with the NDFR attitude display. Each subject saw every experimental condition. The cueing type was pseudo-randomized across attitude display.

The targets originated from azimuths of 0º, ±30º, and ±60º; with elevations of 0º, ±45º. These target locations were repeated for each trial. The location of the target was fixed to the x-axis (nose-to-tail) of the subject's aircraft and did not change when the subjects moved their heads. There were 15 target locations present for each targeting cue and the targets were repeated. Each cue was given for all 15 target locations. Thus for a given attitude display the subject saw 90 targets, 30 for each of the three target cueing types {15 (target locations) x 2 (for repetition) x 3 (for cueing type)}. A Latin square was used to determine the order of the cueing type. The target locations were randomized and the repetition is just the reverse order of the original combinations of target location and cueing type. Between each real target, a dummy target appeared directly in front of the simulated aircraft. This forced the subjects to return their head to boresight between each target, ensuring that every target search began with the subject looking straight ahead. The total number of targets, including dummy targets, seen by a subject throughout the experiment was 360.

Apparatus

The study took place at the Man Vehicle Laboratory, MIT, in Cambridge, MA. The simulation was displayed within a CyVisor HMD, which allows for a 19º by 24º field of view. The subjects were seated in a room with the examiner and had a joystick to fly the simulator. Outside noise was minimized to limit any confusion with the auditory signals. A software package called SLAB provided the auditory cues. Non-individualized HRTFs were used. A HMD with a Flock of Birds magnetic head tracker provided both the attitude displays and the visual cues.

Symbology Sets

Military Standard Head-Up Display (HUD)

The Military Standard HUD, depicted in Figure 5, was used as a baseline comparison with the NDFR display. It includes a climb/dive ladder with flight path marker for attitude reference, an airspeed indicator (left, digital readout with dial and counterpointer), an altimeter (right, digital readout with dial and counterpointer), and a heading tape centered at the top of the screen.

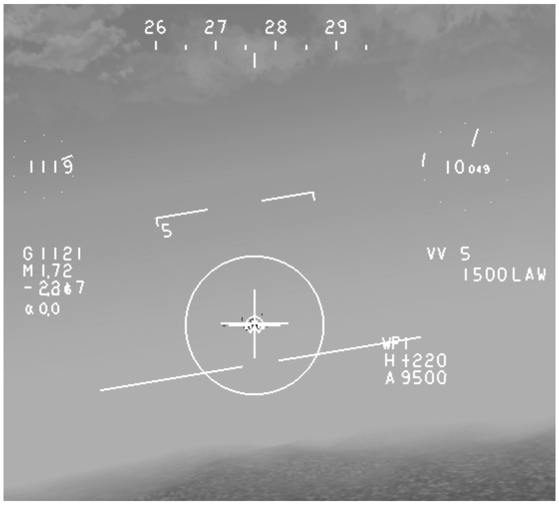

Figure 5: Military Standard Display. In this illustration the simulated aircraft is rolled right less than five degrees, pitched up two degrees, with the airspeed at 1,119 knots, an altitude of 10,049 ft, and a heading of 276 degrees.

<u>Non-Distributed Flight Reference</u>

The NDFR was developed by the Air Force Research Laboratory as a flight reference that has less visual occlusion than other modern symbol sets. The NDFR makes use of the "orange peel" arc for attitude information. Airspeed, heading, and altitude are displayed around a flight path marker to give the pilot all of the ownship status information in a small, well-defined area. The NDFR was flight tested in 2001 aboard a VISTA F-16 equipped with the Viper Mark-IV 40-degree monocular FOV HMD.[6] The recommended changes resulted in the development of the advanced display, a version of which was used in this study. The NDFR display used in the experiment is shown in Figure 6.

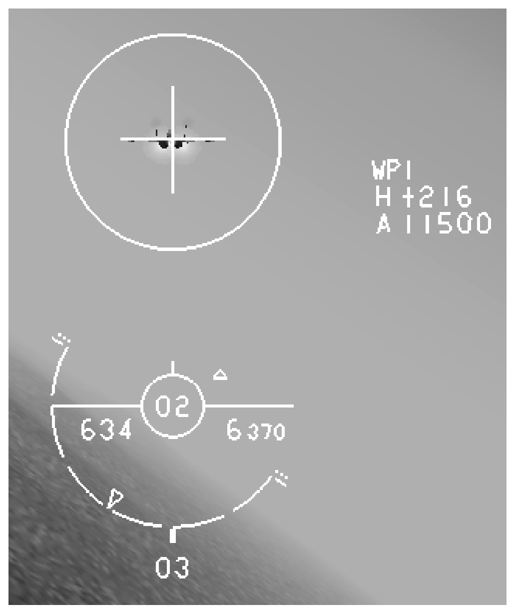

Figure 6: NDFR Display. In this figure, the simulated aircraft is rolled left 30º, pitched up 2º, with an airspeed of 634 knots, an altitude of 6,370 ft, and heading north at 3º.

Visual Cue

The visual cue consists of a single circle with a pointer centered on the aim-sight reticle which is located in the center of the field-of-view. The pointer shows where the subjects should move their head to obtain visual contact with the target aircraft. The visual cue within the aim-sight reticle is shown in Figure 7, in which the target is down and to the right of the subject's current helmet boresight.

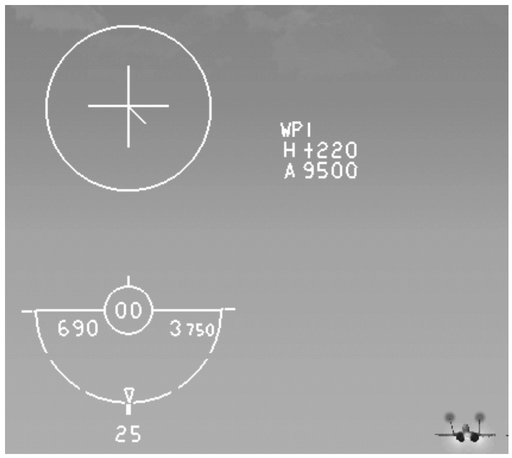

Figure 7: Visual Cue

Auditory Cue

The auditory cue was a female voiced message, "Target-Target," provided through headphones using the SLAB software developed by NASA, which is available to the public. The cue emanated from the same azimuth and elevation as the visual target. The voiced cue had poor resolution in elevation since non-individualized HRTFs were used. The cue ran continuously at a constant frequency, pitch, and volume, and would stop only after the subject visually acquired the target.

Procedure

The subjects were given a set of instructions including a description of the experiment and a set of instructions as to how to interpret the symbology sets. They were told that their objective was to visually acquire a set of targets while maintaining a desired heading and altitude. The flying task was simplified by minimizing the number of controls needed to maintain heading and altitude. The subjects had no rudder pedals and thrust was held constant throughout the entire experiment. The subjects were seated and fitted with the 3-D auditory headphones, the HMD, and the head tracker. Before the recorded trials began they were allowed to fly the simulator with the different attitude displays.

The experiment began after the subject felt comfortable with both attitude displays. The subjects did not have any practice with the target cues. They began the trial at the desired altitude and heading, and were asked to maintain 500 ft for altitude and 20 for heading using joystick inputs. The experiment included simulated turbulence. While maintaining heading and altitude, the subject was required to move his/her head in order to place the target within the aim-sight reticle, i.e., keep the target within five degrees of the center of their field-of-view. Once the subject acquired the target i.e., maintained visual contact with it for three seconds, the target disappeared and a new target appeared. Throughout the trials the subject saw a simulated world that included mountains, fields, and water. The subjects all flew the same flight profile under the same weather and turbulence conditions. After the subjects completed the trial they were asked to fill out a free response subjective questionnaire. The entire experiment lasted approximately 1.5 hours with one hour of actual simulated flying. An explanation of the data analysis done is included in the next section.

RESULTS

The repeated-measures General Linear Model (GLM) Analysis of Variance (ANOVA) was used to determine significant main and cross effects at the $p < 0.05$ level; with a Huynh-Feldt correction applied to the p-values. Statistical analysis was performed using SYSTAT-11 and StatXact-5 Cytel software. The GLM was used to determine the effects of attitude display, target cue, target location, repetition, attitude display order, and flying experience on both flight performance and search time. Two metrics were used to determine flight performance: heading (degrees) and altitude (feet) as deviations from the directed heading and altitude. Search time was determined as the amount of time the subjects took to visually acquire each target by holding it within the aim-sight reticle for three seconds.

Twenty subjects participated in the experiment. Three were removed because they did not finish the experiment, and two others were removed later from the analysis because their data were drastically unlike the other 15 subjects.

Flight Performance Results

The flight performance metrics are the root mean square errors (RMSE) from the commanded heading and altitude, as shown in Equation 1, where the flight metric, *Fm,* is subtracted from the commanded value.

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=0}^{N}\left[\hat{F}_m(z_i) - F_m(z_i)\right]^2} \qquad \text{Eq. 1}$$

For this experiment the commanded heading was 220º and the altitude was 11,500 ft. For both heading and altitude RMSE there was great variation among subjects. No significant ($p < 0.05$) main effects were found by SYSTAT GLM ANOVA. As expected, since the display was helmet-mounted, target cue, target location, and repetition did not have any significant main or cross effects with heading and altitude deviation. Surprisingly, subject flight performance did not change significantly between the Mil-Std and the NDFR displays. Figures 8 and 9 show the average heading and altitude RMSE for all subjects, where attitude display (1) represents Mil-Std symbology data, and (2) represents NDRF results.

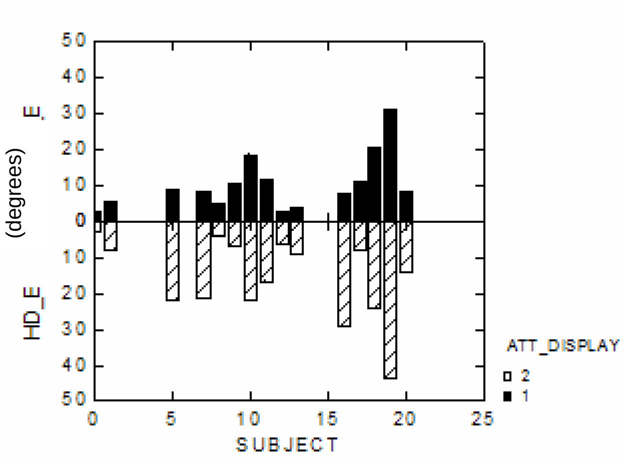

Figure 8: Effect of Attitude Display
Altitude RMSE

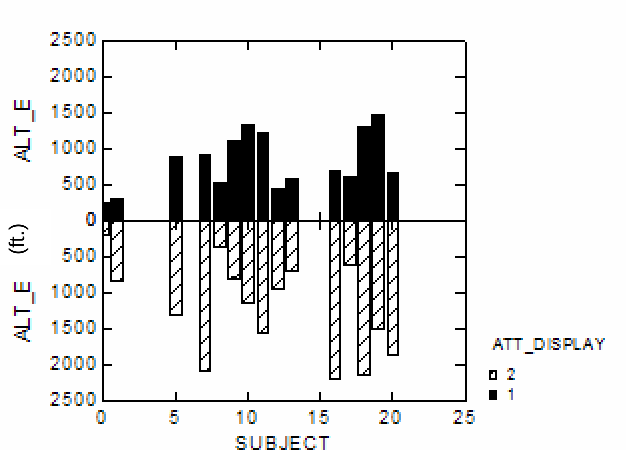

Figure 9: Effect of Attitude Display on
on Heading RMSE.

The overall mean for heading RMSE was 10.502 ±0.356° for the Mil-Std display and 15.675 ±0.531° for the NDFR display. The overall mean for altitude RMSE was 812.934 ±19.846 (ft) for the Mil-Std display and 1214.156 ±34.932 (ft) for the NDFR display. Though these averages seem significantly different they include all other effects and are vulnerable to outliers in the data.

Figures 10 and 11 show the heading and altitude RMSE for a single subject. Throughout the experiment the subjects saw a total of 180 targets, 90 for each attitude display. This target number (1-180) is displayed on the x-axis. Figures 10 and 11 show the data for a subject using Order 1: Mil-Std then NDFR display. For this subject attitude display had no effect on flight performance. The variation for the first 90 targets (Mil-Std) does not differ from the second 90 targets (NDFR). Short of a few outlying points, this trend is consistent across all subjects. There existed a significant cross effect between attitude display, target location, target cue, and order (p = 0.026). When looking closely at the data, this effect is the result of random outliers in the data.

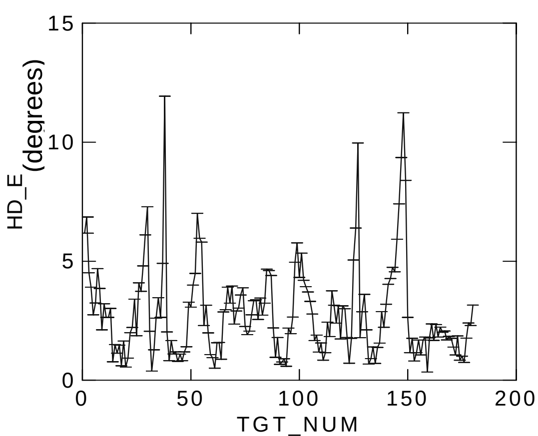

Figure 10: Subject 0 Heading RMSE

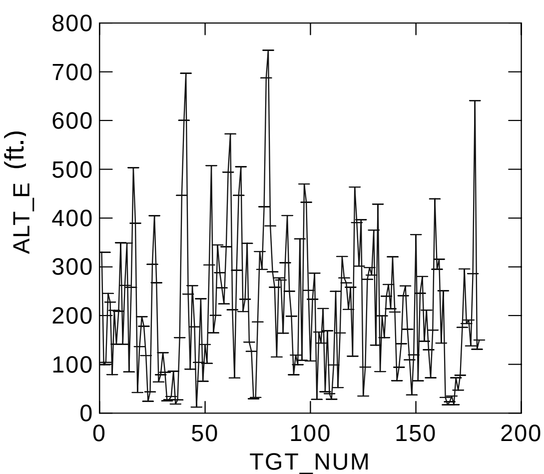

Figure 11: Subject 0 Altitude RMSE

There were no significant main or cross effects of flying experience on either heading or altitude deviation. Both are plotted below in Figure 12. Six subjects had flying experience, four had less than 5 hours and the other two had 40 and 170 hours. The single subject with 170 hours was the only licensed pilot. There was no difference in flight performance among the subjects with 5 hours or less of experience. The subject with 170 hours consistently had one of the lowest heading and altitude RMSE scores and one of the smallest differences between attitude displays. There also existed no difference in performance or preference between the two attitude displays as a function of flying experience. Subject attitude display preference is discussed in further detail in Chapter 5.

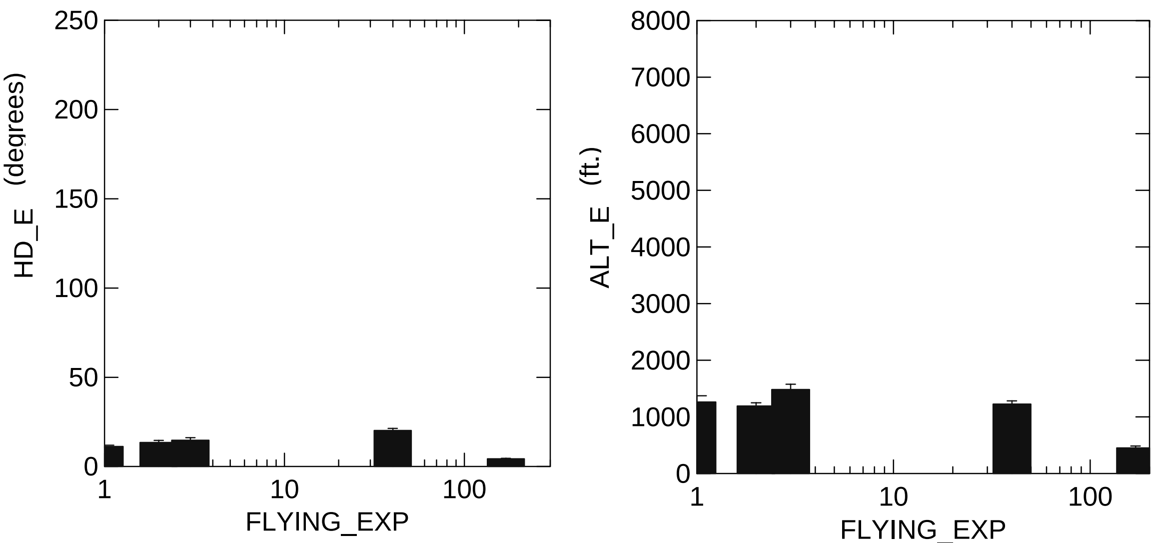

Figure 12: Effect of Flying Experience on Heading and Altitude RMSE

Search Time Results

The significant main and cross effects found for time-to-target, using the repeated measures GLM ANOVA, are listed in Table 2. The first column in the table lists the source of the significant effect, and the second column lists the F-value (F), degrees of freedom (df), and p-value.

Source	(F, df, p-value)
Attitude Display	(21.116, 1, 0.001[i])
Attitude Display*Order	(21.170, 1, 0.001[i])
Attitude Display*Azimuth	(4.578, 4, 0.003)
Attitude Display*Azimuth*Order	(4.551, 4, 0.003)
Elevation*Azimuth	(3.178, 8, 0.004)
Elevation*Azimuth*Order	(2.886, 8, 0.008)
Elevation*Rep*Order	(5.248, 2, 0.013)
Attitude Display*Elevation*Rep	(3.529, 2, 0.045)
Attitude Display*Azimuth*Repetition*Order	(2.864, 4, 0.033)
Attitude Display*Target Cue*Repetition	(7.256, 2, 0.003)
Attitude Display*Target Cue*Repetition*Order	(9.381, 2, 0.001)
Attitude Display*Elevation*Azimuth* Target Cue*Repetition*Order	(2.270, 16, 0.016)

Table 2: GLM Search Time p < 0.05 Results

The only significant main effect found was that of Attitude Display, (p = 0.001). This main effect is plotted in Figure 13 for both between- and within- subjects. Attitude Display (1) is the Mil-Std display while (2) is the NDFR display. The difference in search time varied from subject to subject (right-hand plot below and Table 3). Not all subjects performed better with the NDFR display.

i. Not Huynh-Feldt corrected, df = 1

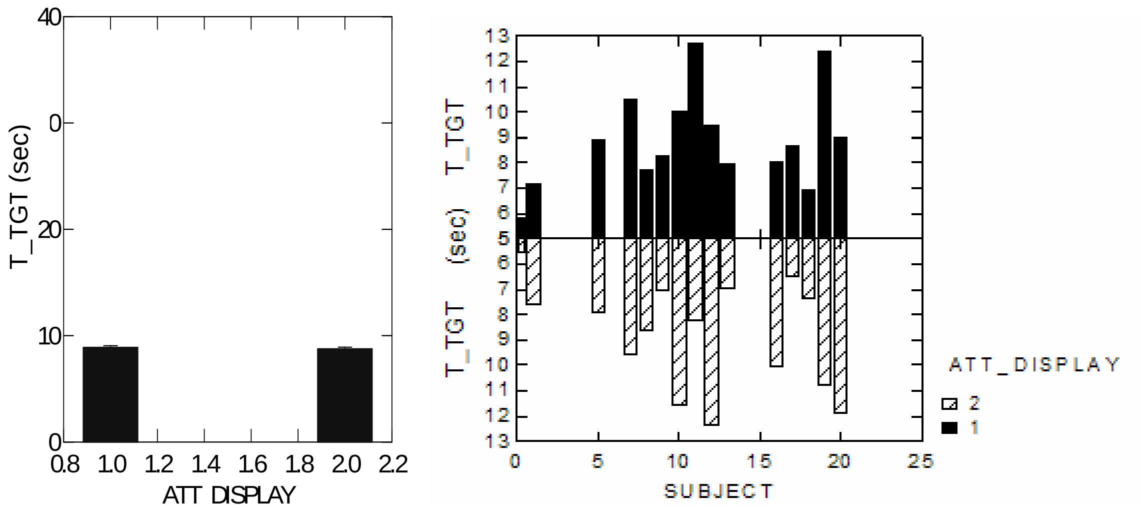

Figure 13: Effect of Attitude Display on Search Time (between, within subjects). The y-axis consists of the time-to-target in seconds. Attitude Display (1) = Mil-Std; (2) = NDFR.

Table 3 shows the averages and differences between attitude displays on time-to-target in seconds for every subject. The difference noted is Military Standard minus NDFR; thus, positive values indicate a reduction in time when using the NDFR display. The significant effect of attitude display on search time is attributable to a few subjects and other effects, e.g., Subject 11 and Order.

Subject	Mil-Std	NDFR	Difference
0	5.83	5.52	0.31
1	7.18	7.60	-0.41
5	8.91	7.88	1.03
7	10.51	9.59	0.91
8	7.71	8.60	-0.89
9	8.30	7.02	1.27
10	9.98	11.51	-1.52
11	12.70	8.18	4.52
12	9.48	12.32	-2.84
13	7.99	6.94	1.06
16	8.07	10.05	-1.98
17	8.67	6.46	2.22
18	6.95	7.36	-0.41
19	12.41	10.71	1.70
20	9.00	11.86	-2.86
Overall	**8.91**	**8.77**	**0.14**

Table 3: Time-to-Target Averages between Attitude Displays (sec) SE = ±0.15

The cross effect, Attitude Display and Order, was also found to be significant. Figure 10 shows the overall effect of Attitude Display and Order, while Figure 11 shows the difference in search time between the Mil-Std and NDFR displays for each subject. Order (1) refers to sequence Mil-Std:NDFR, while (2) refers to NDFR:Mil-Std.

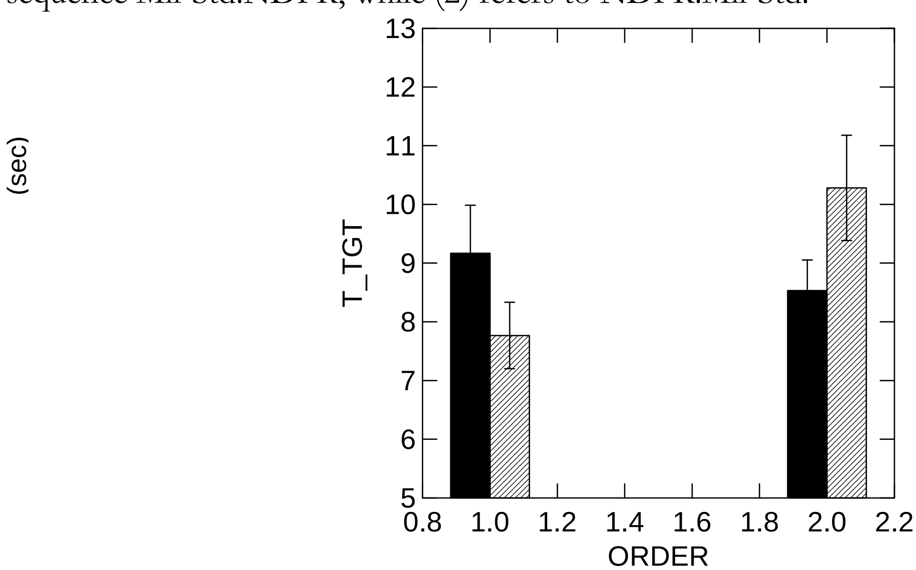

Figure 14: Cross Effect of Attitude Display and Order (1,2) = ({Mil-Std:NDFR},{NDFR:Mil-Std}). The solid bar = Mil-Std, hash bar = NDFR.

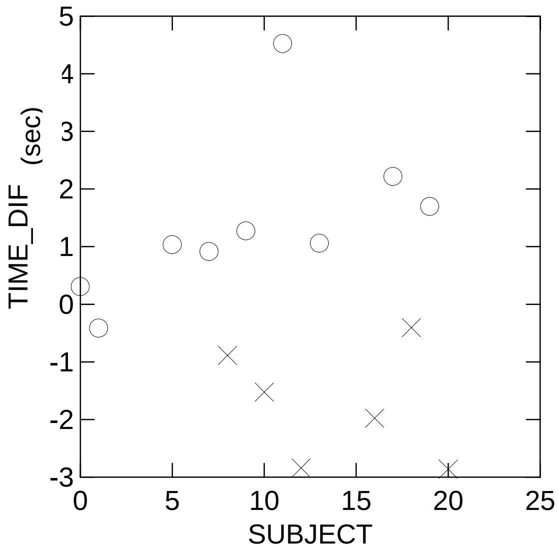

Figure 15: Cross Effect of Attitude Display and Order. Y-axis is the difference in search time between Mil-Std and NDFR (i.e., Mil-Std – NDFR). Shape depicts Order (1,2) = (O, X).

The significant cross effect of Attitude Display * Order ($p = 0.001$) is consistent with a learning effect. The subjects always performed better with the second display presented. Figure 11 shows that the difference between displays is smaller for subjects who started the simulation with the Mil-Std display and ended with the NDFR. The average difference between the first display and the second for Order (1) is 1.401 ±0.2 s, while the average for Order (2) is 1.745 ±0.35 s. From this point the cross effect of Attitude Display * Order (as it is called in the analysis) will be referred to as the First Display effect.

Two cross effects, (1) Attitude Display * Azimuth, and (2) First Display * Azimuth, were found to be significant at $p = 0.003$. The plots below show the combined effects of these factors within each subject. The x-axis is the target azimuth and ranges from 0-4 (-60º, -30º, 0º, +30º, +60º). The y-axis shows the difference between the NDFR and Mil-Std displays. The order is coded into the subject number which is located on top of the plot. Subjects with odd numbers flew the simulation with Order 1 (Mil-Std:NDFR), while those with even numbers flew with Order 2 (NDFR:Mil-Std). The biggest difference between the NDFR and the Mil-Std display occurs at Azimuth 3 (+30º). The difference is negative for subjects in Order (1) and positive for Order (2). This is similar to the effect seen above in that the second display resulted in faster search times. The result for Azimuth 3 is significantly different ($p = 0.008$) from the average of the other four Azimuths, 0-2, and 4.

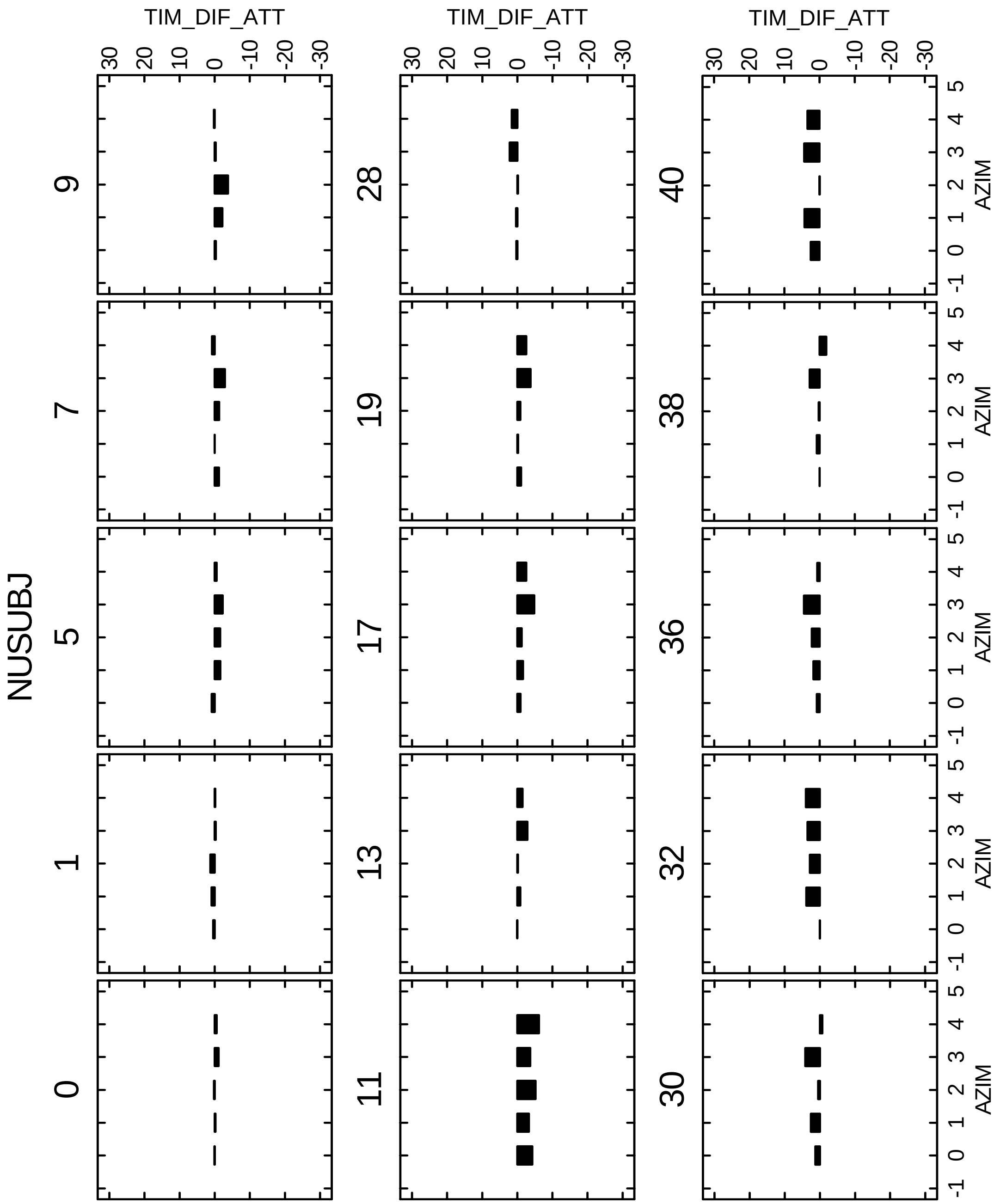

Figure 16: Cross Effect of Attitude Display, Order, and Azimuth on Search Time

The effect of target location (embracing both elevation and azimuth) and target location * order were found to be significant (p = 0.004, 0.008). Figure 15 shows the average effect, across all subjects, of target location on search time. The target locations are separated into three groups of five representing the three elevations (+40º, 0º, -40º) and five azimuths (-60º, -30º, 0º, +30º, +60º). The vertical lines in the plot below denote the three elevation angles +40º, 0º, and -40º. Within each elevation group the azimuths range from -60º to +60º. No significant main effects were found on time-to-target for azimuth or elevation. There is a significant difference between the target locations at 0º elevation and ±40º, but no difference between +40º and -40º elevations (p = 0.0005). Order 2 gave slower search times than Order 1 for almost all target locations.

Elevation had a significant cross effect with Repetition and Order (p = 0.013) as well as Repetition and Attitude Display (p = 0.045) on search time. The difference between the first and second repetitions at an elevation of -40º for Order (2) was greater than the rest, 3.874 ±0.591 s. The difference between repetitions was also greater at the same elevation for the Mil-Std display, 3.367 ±0.488 s. In both cases the second repetition had a faster search time. Figure 16 shows the cross effect of Elevation, Repetition, and Order on search time. The x-axis represents the elevations (+40º, 0º, -40º) and the y-axis shows the difference between the second and first repetitions.

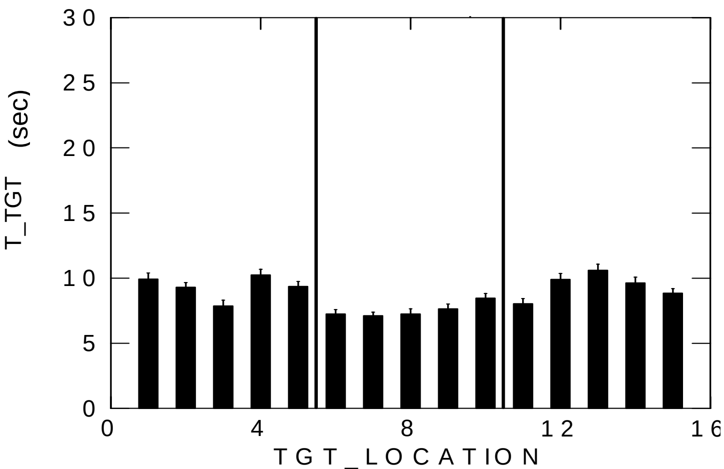

Figure 17: Effect of Target Location on Search Time

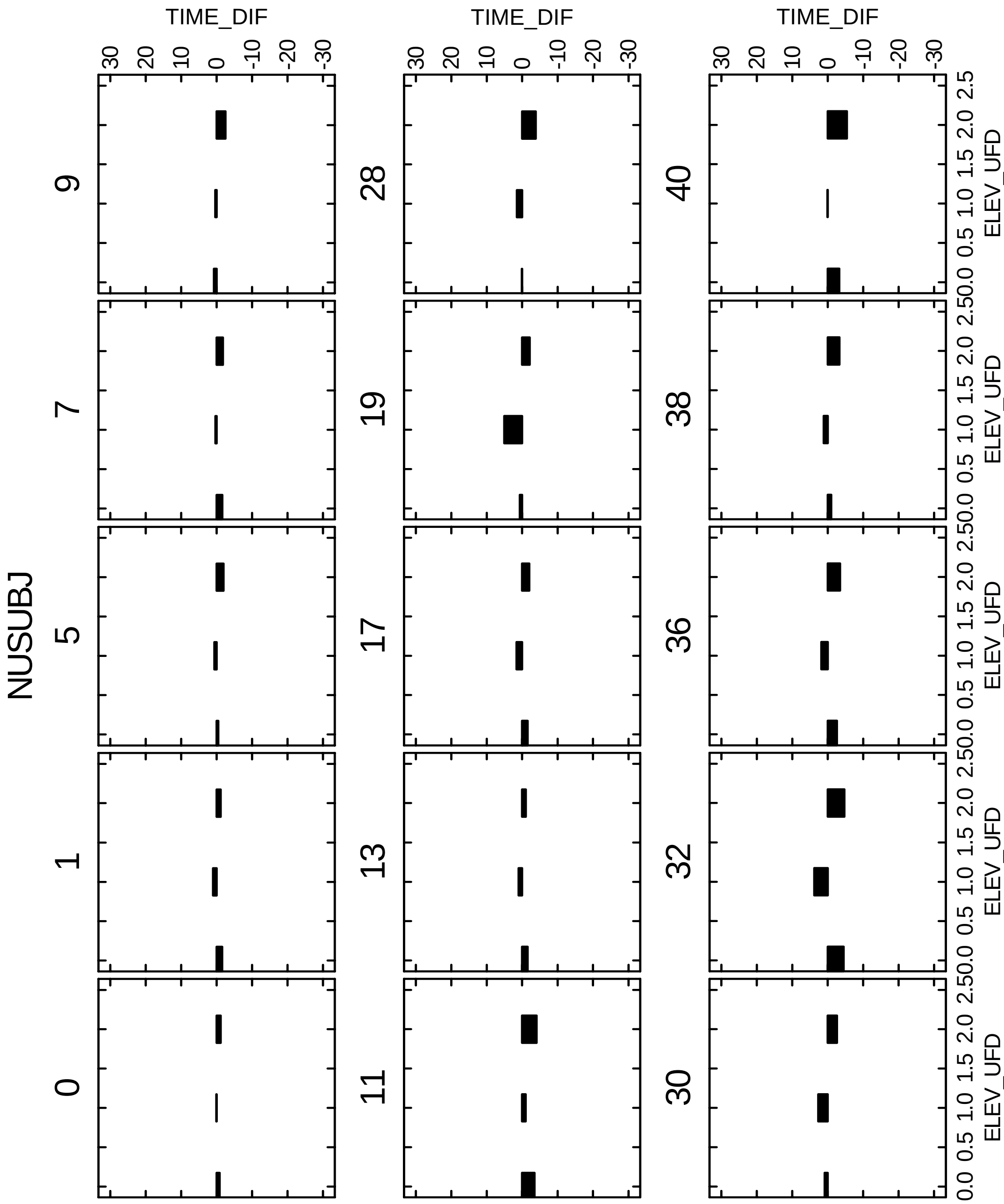

Figure 18: Cross Effect of Elevation, Repetition, and Order on Search Time

A repeated-measures GLM ANOVA analysis found no significant main effect of target cue on search time. Figure 17, however, shows the effect of target cue on search time and the trend is significant [$p <$ 0.00005 by the non-parametric Page Test (StatXact-5, Cytel), from slowest to fastest search times: Audio Only (10.260 ±0.221s), Visual Only (8.772 ±0.178s), Combined Visual/Audio (7.497 ±0.128s)], and holds for all but two of the subjects, 0 and 8.

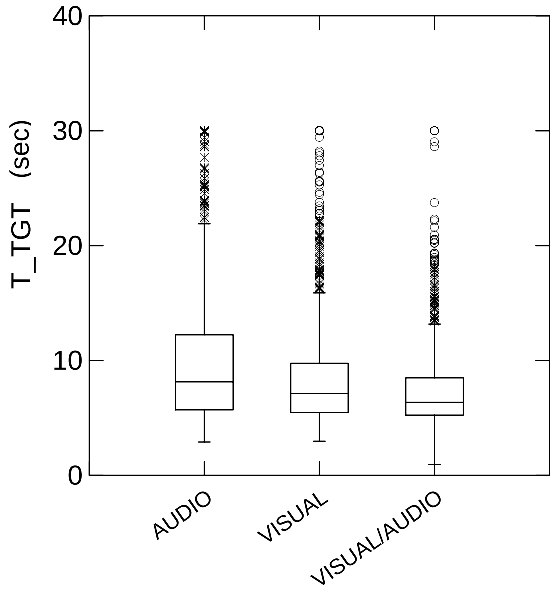

Figure 19: Box plots depicting effect of Target Cue on Search Time. The box plots show the median (line through box), 25% quartile (bottom of box), and 75% quartile (top of box); data that are more than three standard deviations from the average are shown outlying points beyond the legs.

The last four seemingly significant cross effects, or (1) Target Cue * Repetition * Attitude Display (p = 0.003); (2) Target Cue * Repetition * First Display (p = 0.001); (3) First Display * Azimuth * Repetition (p = 0.033); and (4) First Display * Elevation * Azimuth * Target Cue * Repetition (p = 0.016) can be attributed to a few outliers in the data.

DISCUSSION

The results of this experiment showed that there was no difference in flight performance between the Military Standard and Non-Distributed Flight Reference displays. There existed a strong learning effect on search times affected by the order in which the attitude displays were presented. It was easier for subjects to transition from the Military Standard to the NDFR than in the opposite order. The greatest difference between attitude displays on search time existed at an azimuth of +30º, while the fastest search times occurred at target locations within the 0º elevation angle. The difference between repetitions was greatest at an elevation of 0º, with the second order, and Mil-Std display. Target cue had a significant effect on search time with the audio only condition the slowest, then the visual only condition, and the combined condition the fastest.

This experiment finds no effect of display (Military Standard vs. Non-Distributed Flight Reference) on heading and altitude RMSE. This result is consistent with the experiments of Geiselmen et al.[2] and Jenkins et al.[4] where no difference in flight performance was found when using the NDFR display. Between this experiment and past research the NDFR is proving to be an effective attitude display for visual search tasks. It was viewed by the subjects to be a "cleaner and more integrated [display, but] more challenging to use." It provided attitude information quickly, but took the subjects longer to become accustomed to using it, translating the arc into pitch and bank information. Some subjects complained that the Military Standard display contained too many moving segments that took up much of the visual space, distracting them from finding the targets. In the end the NDFR display takes more time to become accustomed to but provides adequate information in a clean and integrated display, while the Mil-Std is more intuitive when controlling pitch and bank but requires a longer visual scan to obtain necessary attitude information. Future work should focus on improving the NDFR's ability to display bank and pitch information. Two possible improvements include broadening and/or lengthening the 0º pitch lines and including a horizon line at 0º pitch.

The time-to-target was affected by both the attitude display used and the order in which it was presented. The longer visual scan required by the Mil-Std display may explain why use of the NDFR display resulted in faster search times. Subjects who were presented with the attitude displays in the second order (NDFR:Mil-Std) had a greater reduction in search time. The simulated aircraft was easier to control with the Mil-Std display. Thus, the subjects seeing that display second had an easier display to work with when they were more familiar with the experiment.

The difference between the second and first attitude displays was found to be most sensitive at the +30º azimuth. The subjects had the greatest reduction in search time for the faster display at this azimuth. Although it is possible that subjects began their visual searches to the right, more analysis is needed to resolve this apparent preference in azimuth.

It comes as no surprise that the fastest search times occurred at 0º elevation ($p < 0.0005$), closest to the center of the subject's FOV. Another possible reason for this finding is that the audio cue for these targets was not required to provide any up-down information. This poor resolution in elevation for the audio cue will be discussed later. The first repetitions for targets located at -40º elevation were found to have the greatest search times ($p < 0.05$). At the start of the experiment, subjects did not tilt their head down enough to acquire the lowest targets efficiently during their visual search. Once the subjects became accustomed to the target location extremes the search time for targets located below their horizon decreased significantly.

This study found a significant effect of target cue on search times. The three target cues studied were: (1) 3-D audio only, a voiced signal = "Target-Target"; (2) visual only, a line emanating from aim-sight reticle pointing towards target aircraft; and (3) a combined audio/visual cue, providing both cues. Use of the 3-D audio only cue resulted in the longest search times, on average 10.26 seconds, which was 1.5 seconds longer than the visual only condition and 2.8 seconds longer than the combined cue. These results are consistent with the findings of Begault et al.[12] and Simpson et al.[13] where a combined audio/visual system performed better than either audio or visual cueing alone for the TCAS and TAS. Humans are known to process audio information faster than visual. However, during a high workload task where spatial information needs to be derived from the audio signal, audio information will not always be processed faster than visual. Increase in cognitive demand may be one reason that the audio cue produced slower results than the visual. Another cause for the same trend may be the limitation of using non-individualized HRTFs, which are known to degrade elevation resolution.[8] The majority of the subjects commented on the fact that they had difficulty interpreting the audio cue when the targets were located at ±40º elevation for any azimuth, with the greatest difficulty occurring at 0º azimuth.

CONCLUSIONS

The NDFR display has been shown to be as effective as the current Mil-Std display in providing attitude information. The cleaner, more integrated display of the NDFR provided subjects with all the needed attitude information while reducing their visual search time. Though more training may be required to become accustomed to the NDFR display, its ability to provide attitude information quickly to the pilot when looking on or off-boresight may help reduce spatial disorientation. This experiment required the subjects to fly a simple straight and level flight; future work should look into the benefits of the NDFR display during a more dynamic flight profile.

Using the Non-Distributed Flight Reference display for attitude information combined with a 3-D audio/visual cueing system for target acquisition is a promising method of reducing search time during a visual search task. Although this experiment did show that a combined audio/visual cueing system was faster than either alone, future experiments should incorporate all of the lessons learned from past localized audio research. In this experiment the voiced cue did not contain elevation information that has proven to be effective in past experiments.[13] As the Air Force moves forward in improving visual systems, including localized audio cues, and developing tactile sensors, more research should be conducted that incorporates these three media.

REFERENCES

1. Geiselman, E.E. and Osgood, R.K., (1994). Utility of off-boresight helmet-mounted symbology during a high angle airborne target acquisition task. *Helmet- and Head-Mounted Displays and Symbology Design Requirements*. Lewandowski, R.J., Stephens, W., and Haworth, L.A. (Eds.), The International Society for Optical Engineering. Bellingham, WA., pp. 328-338.

2. Geiselman, E.E., Havig, P.R., and Brewer, M.T., "A non distributed flight reference symbology for helmet-mounted display use during off-boresight viewing: development and evaluation," *Helmet and Head-Mounted Displays V*. Lewandowski, R.J., Haworth, L.A., and Girolamo, H.J. (Eds.), The International Society for Optical Engineering. Bellingham, WA, pp. 272-283, 2000.

3. Havig, P.R, Jenkins, J.C., Geiselman, E.E., "A Comparison of HMD Ownship Status Symbology and Frame of Reference Orientation During Two Aircraft Control Tasks." Air Force Research Laboratory, WPAFB, OH.

4. Jenkins, J. C., Thurling, A. J., Havig, P. R., and Geiselman, E. E., "Flight test evaluation of the non-distributed flight reference off-boresight helmet-mounted display symbology," *Proceedings of SPIE, Helmet-Mounted Displays VII, Lewandowski, R. J., Haworth, L. A., and Girolamo, H. J. (Eds)*, SPIE, Bellingham, Washington, pp. 341-355, 2002.

5. Jenkins, J.C., Maj. Thurling, A.J., Brown, B.D., "Ownship status helmet-mounted display symbology for off-boresight tactical applications." Air Force Research Laboratory, WPAFB, OH.

6. Geiselman, E.E., et al.. "Methodology for Evaluating Off-Axis Helmet-Mounted Display Ownship Information."

7. Begault, D. R., Wenzel, E. M., and Anderson, M. R. "Direct Comparison of the Impact of Head Tracking, Reverberation, and Individualized Head-Related Transfer Functions on the Spatial Perception of a Virtual Speech Source." J. Audio Eng. Soc Vol. *49*, No. 10, 2001.

8. Bolia, R.S., D'Angelo, W.R., & McKinley, R.L. "Aurally Aided Visual Search in Three-Dimensional Space." *Human Factors*, 41(4), 664-669, 1999.

9. Flanagan, P., McAnally, K.I., Martin, R.L., Meehan, J.W., & Oldfield, S.R. "Aurally and Visually Guided Search in a Virtual Environment." *Human Factors,* 40(3), 461-468, 1998.

10. Nelson, W. T., et al.. "Effects of Localized Auditory Information on Visual Target Detection Performance Using a Helmet-Mounted Display." *Human Factors*; Sep 1998; 40, 3; ProQuest Psychology Journals, pg. 452.

11. Begault, D.R, and Pittman, M. T. "Three-Dimensional Audio Versus Head-Down Traffic Alert and Collision Avoidance System Displays." *The International Journal of Aviation Psychology*, 6(1), pgs. 79-93, 1996.

12. Begault, D.R, Wenzel, E.M., and Lathrop, W. B. "Augmented TCAS Advisories Using a 3-D Audio Guidance System." Proceedings of the Ninth International Symposium on Aviation Psychology. Ohio State University, Columbus, OH, 1997.

13. Simpson, B.D. et al.. "3D Audio Cueing for Target Identification in a Simulated Flight Task." Air Force Research Laboratory, Wright-Patterson Air Force Base, OH. 2004

14. Nelson, W. T., et al.. "Localization of Virtual Auditory Cues in A High +Gz Environment." Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting, 97-101. 1998.

APPENDIX A
Consent Form

CONSENT TO PARTICIPATE IN NON-BIOMEDICAL RESEARCH

COMBINED EFFECTS OF A 3-D AUDITORY/VISUAL CUEING SYSTEM AND THE NON-DISTRIBUTED FLIGHT REFERENCE ON VISUAL TARGET DETECTION USING A HELMET-MOUNTED DISPLAY

You are asked to participate in a research study conducted by L. Young, Sc.D. and C. Pinedo, from the Aero/Astro Department at the Massachusetts Institute of Technology (M.I.T.) The results of the study will contribute to thesis work done by Carlos Pinedo. You were selected as a possible participant in this study because you are 18 years of age or older and have no serious sight or hearing impairments. You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

- **PARTICIPATION AND WITHDRAWAL**

Your participation in this study is completely voluntary and you are free to choose whether to be in it or not. If you choose to be in this study, you may subsequently withdraw from it at any time without penalty or consequences of any kind. The investigator may withdraw you from this research if circumstances arise which warrant doing so.

- **PURPOSE OF THE STUDY**

It is the objective of this study to investigate the combined benefits of the Non Distributed Flight Reference (NDFR) symbology developed by the Air Force and a 3-D audio/visual cueing system for target acquisition tasks in a stationary simulator using a helmet mounted display (HMD).

- **PROCEDURES**

If you volunteer to participate in this study, we would ask you to do the following things:

The study will begin with a quick Powerpoint presentation that describes in greater detail the attitude displays and cueing system. After finishing the presentation you will be asked to fly two practice runs so as to become familiar with the two attitude displays. Once you feel comfortable with the system the experiment will begin.

You are asked to fly two trials where you will visually acquire 360 targets. The simulation will be displayed using a helmet mounted display system. The audio cues will be given through headphones.

During each trial you are to fly through a series of waypoints. Optimum performance is defined as flying straight from the center of one waypoint to the center of the next waypoint. During the flight you will be asked to locate and indicate a series of aerial targets. You will be notified that you have acquired a target and can begin locating the next target. Your flight performance, as well as your time to acquire a target will be measured. Head movement and velocity will be measured to study search strategies.

The two trials are scheduled to take no longer than thirty minutes each. After completing the trials you will be asked to fill out a subjective questionnaire to help us better understand how adequate the systems are. The entire study should take no longer than 1.5 hours.

- **POTENTIAL RISKS AND DISCOMFORTS**

Due to the nature of the experiment you may begin to feel motion sick. If flying the simulator is making you feel motion sick please respond verbally that you would like to stop the simulation.

- **POTENTIAL BENEFITS**

The study posses no potential benefits to you as a subject, however, your participation in this study is greatly appreciated. This research may potentially help combat spatial disorientation in high performance aircraft as well as help design systems that increase the performance of pilots in fighter aircraft.

- **PAYMENT FOR PARTICIPATION**

For participation in this study you will receive a payment of $10.00/hr.

- **CONFIDENTIALITY**

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law.

No personal information will be kept. You will be assigned a number so as to keep track of the data. The data itself will be disclosed only to members of the Man Vehicle Lab and the Air Force Research Lab located at Wright Patterson AFB.

All electronic data will be kept on a password protected computer. All other information will be kept in the experimental room, which is always locked.

- **IDENTIFICATION OF INVESTIGATORS**

If you have any questions or concerns about the research, please feel free to contact Carlos Pinedo, astech@mit.edu.

- **EMERGENCY CARE AND COMPENSATION FOR INJURY**

In the unlikely event of physical injury resulting from participation in this research you may receive medical treatment from the M.I.T. Medical Department, including emergency treatment and follow-up care as needed. Your insurance carrier may be billed for the cost of such treatment. M.I.T. does not provide any other form of compensation for injury. Moreover, in either providing or making such medical care available it does not imply the injury is the fault of the investigator. Further information may be obtained by calling the MIT Insurance and Legal Affairs Office at 1-617-253 2822.

- **RIGHTS OF RESEARCH SUBJECTS**

You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E32-335, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253 6787.

SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE

I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

____

Name of Subject

____

Name of Legal Representative (if applicable)

____ ______________

Signature of Subject or Legal Representative Date

SIGNATURE OF INVESTIGATOR

In my judgment the subject is voluntarily and knowingly giving informed consent and possesses the legal capacity to give informed consent to participate in this research study.

____ ______________

Signature of Investigator Date

APPENDIX B
Subjective Questionnaire

Pilot_______

COMBINED EFFECTS OF A 3-D AUDITORY/VISUAL CUEING SYSTEM AND THE NON-DISTRIBUTED FLIGHT REFERENCE ON VISUAL TARGET DETECTION USING A HELMET-MOUNTED DISPLAY

Thank you again for participating in this study please fill out the information below:

Age _______

How often do you play video games?

- ☐ Never
- ☐ Daily
- ☐ Weekly
- ☐ Monthly

Gender

- ☐ Male
- ☐ Female

Dominant Hand:

- ☐ Right Hand
- ☐ Left Hand

Flying Experience

- ☐ No previous flying exerperience
- ☐ Prior Flying Experience
  - ☐ Aircraft
    # of hours____________
  - ☐ Helicopter
    # of hours____________

Do you use any corrective eye wear?

- ☐ None
- ☐ Eye glasses
- ☐ Contacts

Are you wearing any corrective eye wear now?

- ☐ Eye glasses
- ☐ Contacts

Have you ever suffered from hearing loss or have any hearing impairments?

- ☐ Yes
- ☐ No

APPENDIX C
Flight Performance Data All Subjects

Heading RMSE Plots

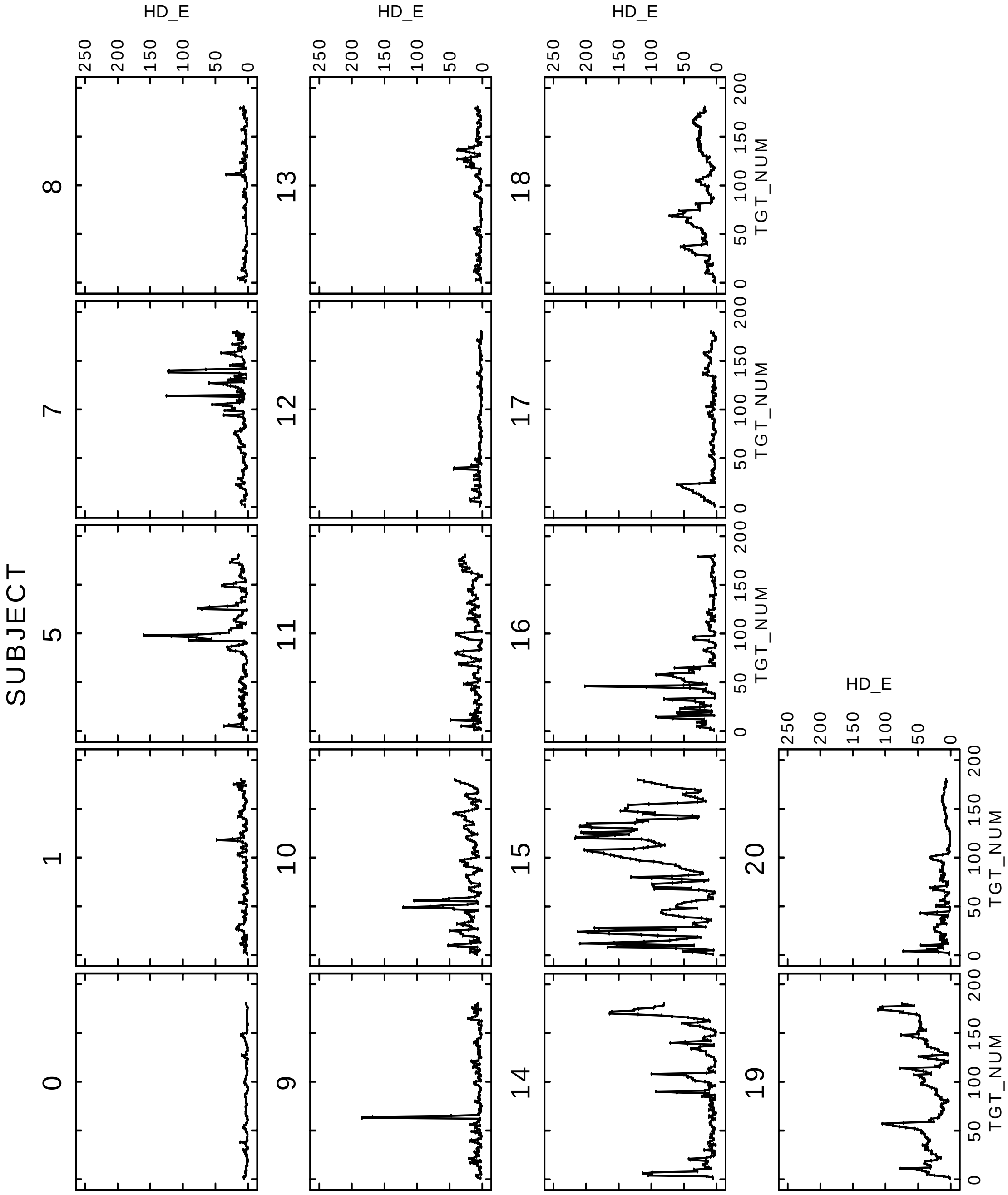

Figure 20: Subject Heading RMSE over Entire Experiment

Altitude RMSE Plots

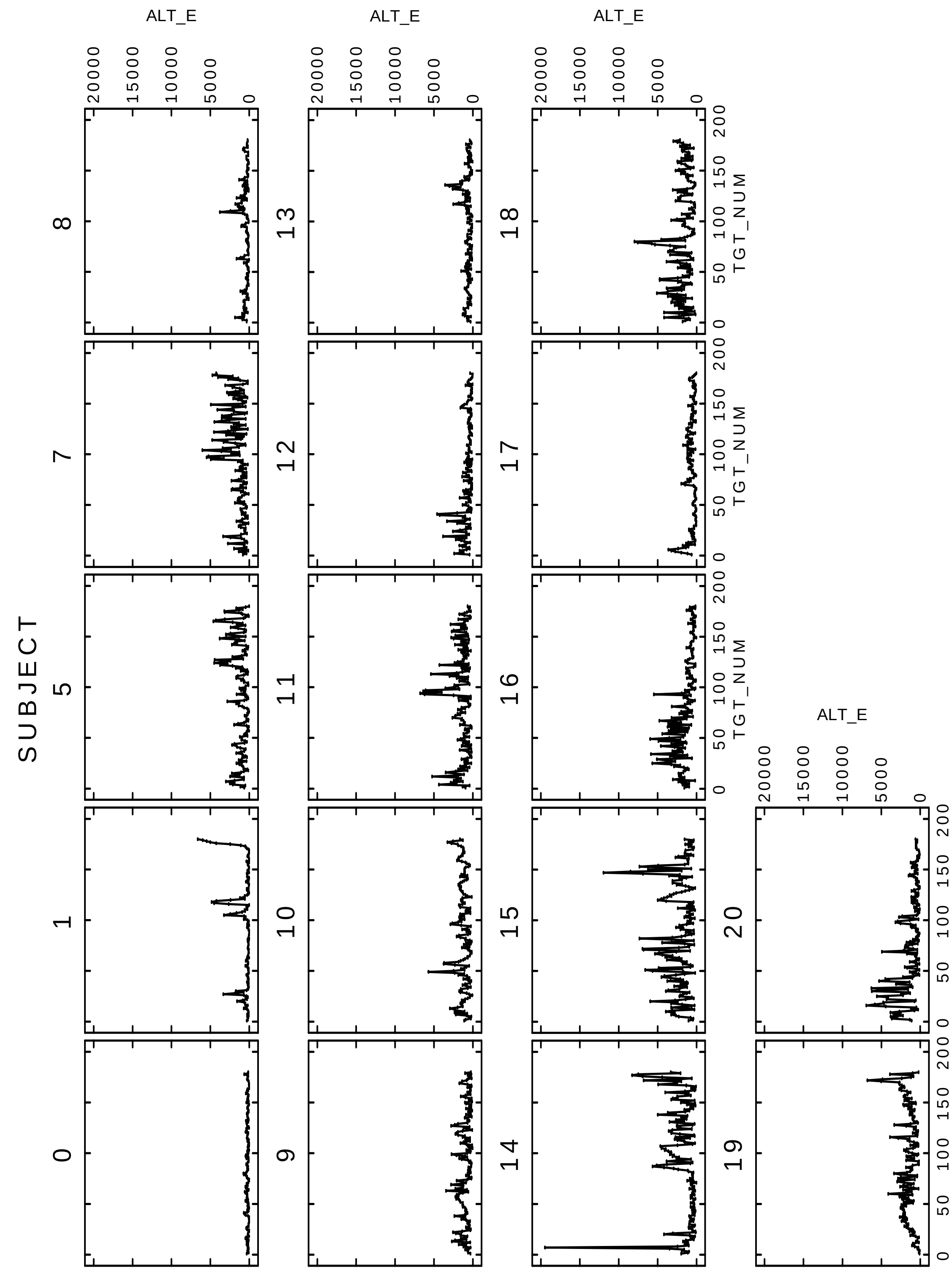

Figure 21: Subject Altitude RMSE

Search Time Results

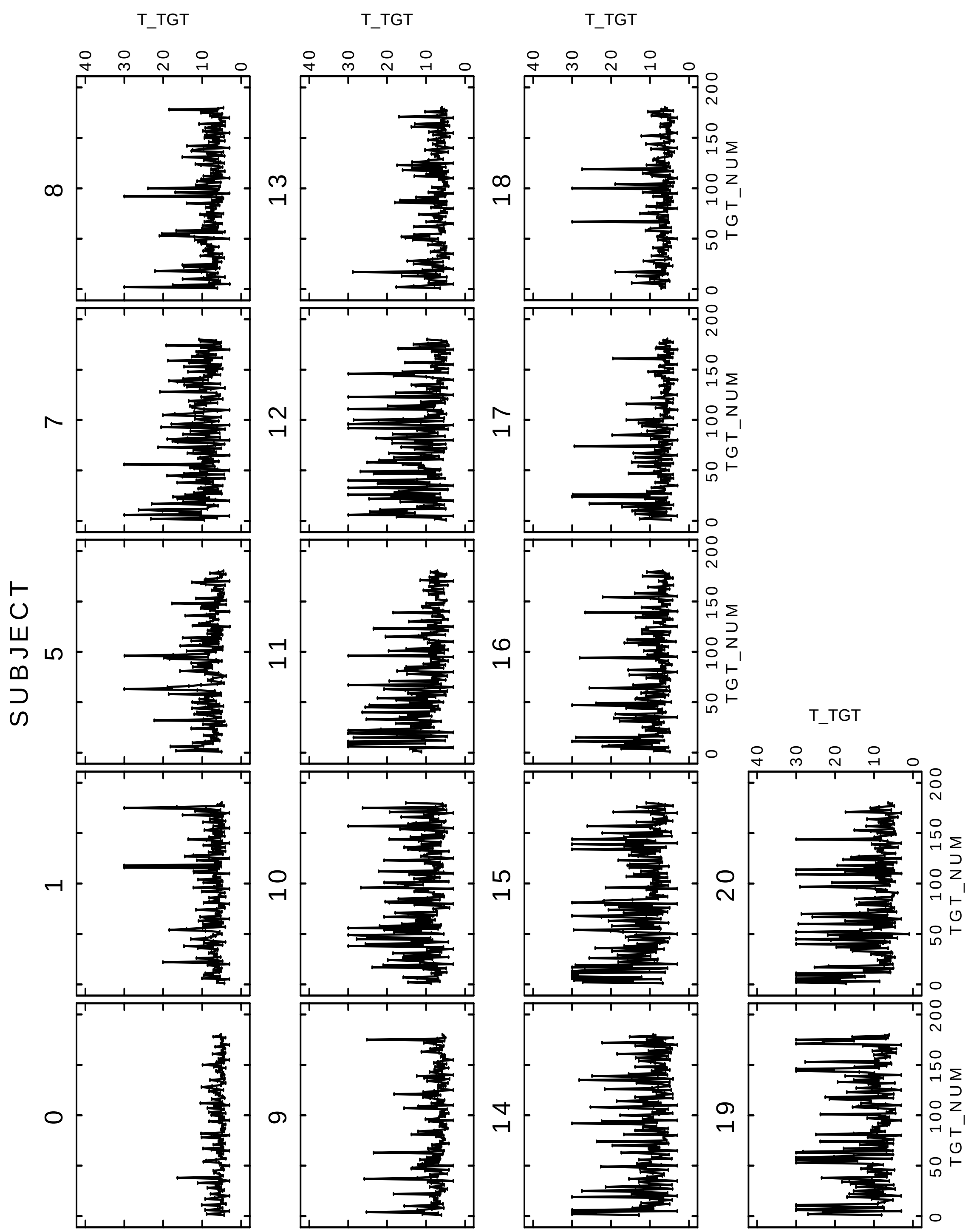

Figure 22: Subject Search Time for All Targets

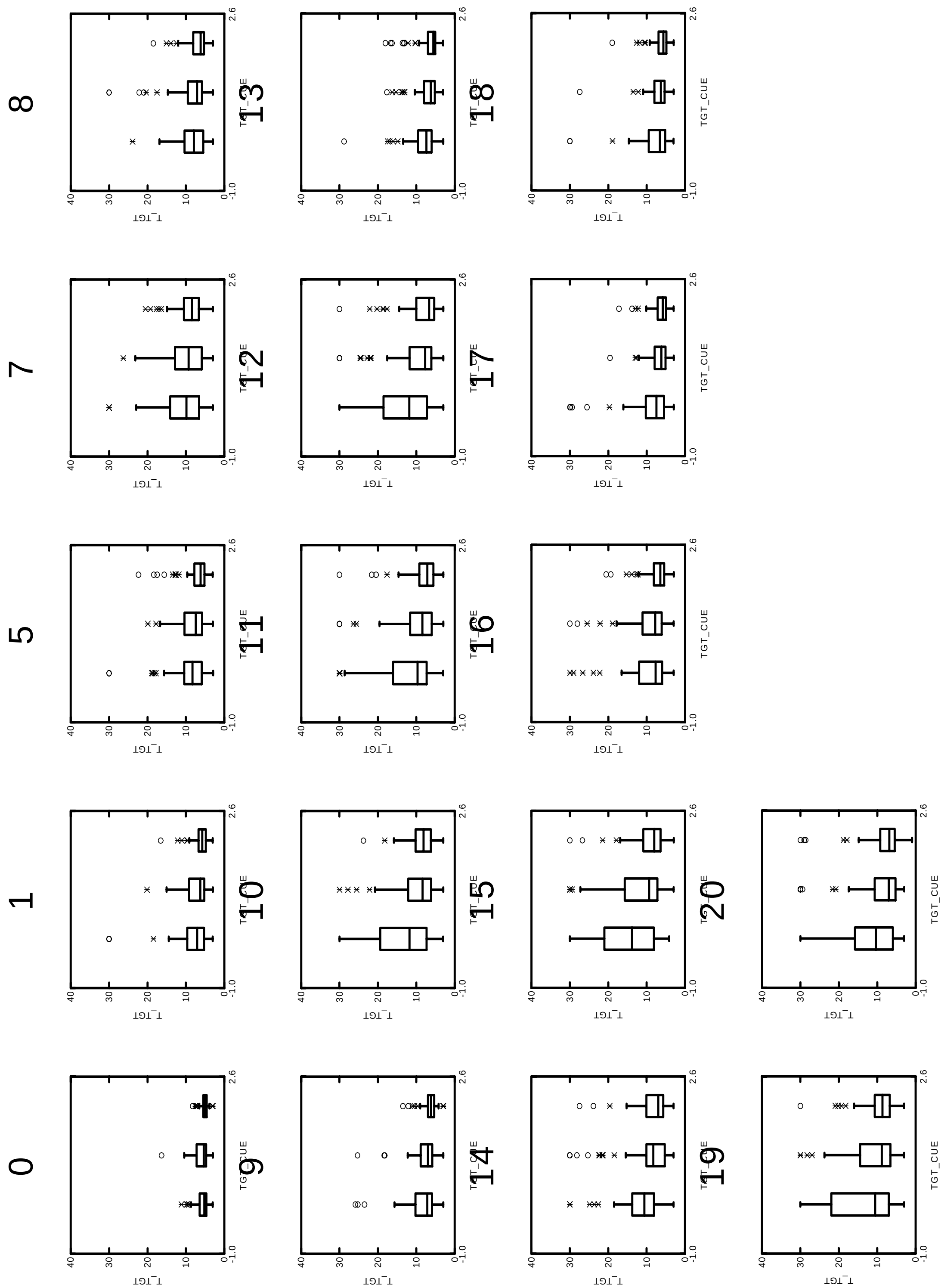

Figure 23: Effect of Target Cue on Search Time for All Subjects